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A state of art review on recycling and remanufacturing of the carbon fiber from carbon fiber polymer composite

Muhammad Ateeq

Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Carbon fiber reinforced polymer composites (CFRPC) are commonly used in various applications like sports, aviation, transportation, and the building sector. In particular, CFRPC preparations (intermediate products) are employed in CFRPC manufacturing, with much waste being generated through fabrications procedures and after its life cycle. Recovering of the carbon fiber from the waste of the CFRPC is a serious challenge for the renewable energy division. This paper describes an advances in the different recycling techniques of the recycled carbon fiber from the carbon fiber polymer composites and re-manufacturing of the recovered carbon fiber from the recycling technique into three-dimensional printed composite products. Physical and mechanical properties of the recovered carbon fiber printed using the different polymers matrix materials have been discussed. The aim of this paper also includes present problems and developments in the disposal and reuse of fiber-reinforced composites. Overall, the research presented in this paper gives valuable insights into the recycling techniques of carbon fiber and remanufacturing of the recovered carbon fiber for society's long-term development. After a thorough review of the available literature, study gaps are identified in order to determine future paths in this work.

1. Introduction

The growing need for novel and creative materials with features such as lightweight and excellent strength in the aerospace and automotive sectors has prompted researchers and engineers to employ polymer composites as viable substitutes for metal components that have emerged in the past several years [1–4]. From the different polymer matrix composites, the carbon fiber-based polymer composites offer a significant contribution toward the polymer matrix composites in the various applications. Because carbon fibers provide great strength, high specific modulus, excellent resistance to temperature, outstanding electrical conductivity, etc., and have become popular in the modern manufacturing industry as an essential component in producing innovative composite materials. Carbon fiber is also a one-of-a-kind material with a high strength-to-weight ratio, low environmental impact, recycling, noncorrosive properties, and exceptional wear resistance. Carbon fiber utilized by the industries includes metal matrix composites, ceramic matrix composites, and polymer matrix composites, the most common of which are CFRPC [5].

Carbon fiber was created by using thermal processing and oxidation at high temperatures by carbonizing rayon or pitch resin and synthetic polymers. Extremely high temperatures were utilized to carbonize the carbon fiber, leading to a higher carbon element concentration in the finished product. Carbon fiber can be divided into continuous and discontinuous types based on the carbon fiber length or the fiber orientation within the matrix [6]. CFRPC materials are widely applied in various sectors, such as air, land, and sea automobiles, wind turbines, storage tanks, and sporting goods [7–11]. In China, using the carbon fiber percentage in the different industries based on 2020 data is illustrated in Fig. 1. CFRP offers considerable weight savings since a CFRP component is 25–30 % lighter than an ordinary metal component [12]. Compared with steel automotive components, CFRP can yield weight reductions of up to 65 % [13] and up to 20 % when substituting aluminum in aviation [14]. The demand for carbon fiber is increasing daily due to its vast application in different sectors [15], leading to the required higher volume production of virgin carbon fiber. Manufacturing of the virgin carbon fiber (vCF) involves a lot of power. Based on the Japan Carbon Fiber Manufacturers Association (JCMA), the power usage for creating vCF is around 290 MJ/kg, resulting in a significant vCF price [16].

On the other hand, the widespread use of this material has resulted in tremendous energy and material usage throughout the manufacturing

E-mail addresses: 22107706r@connect.polyu.hk, ateeqmuhammad93@gmail.com.

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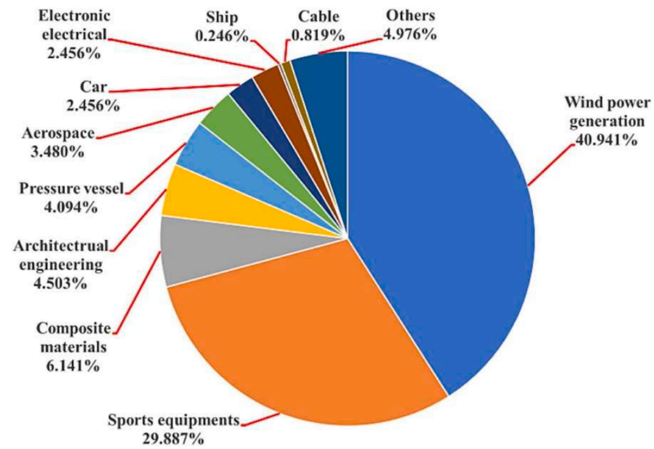

Fig. 1. Percentage utilization of the CFRP in the different sectors. Reproduced with permission from Elsevier [5].

process as well as the release of considerable capacities of trash. The higher price and energy consumption required to produce the vCF offers the utilization of the recovered carbon fiber after its life cycle, reducing the environmental impact and land usage owing to its waste. In addition, with an estimated market size of $40 billion, the worldwide CFRP demand has risen at an average yearly growth rate of around 12 % since 2010 [17]. Because nearly 40 % of all virgin carbon fiber is thrown in as material offcuts, worldwide demand for carbon fiber is expected to outstrip the worldwide supply by 2030 [18,19]. The commercial aeronautical and wind power sectors are anticipated to contribute around 97,000 tons of CFRP garbage to landfills by 2044 in China. In contrast, 22,000 tons of waste is generated from aeronautical, and about 75,000 tons of waste is caused by the wind power sector [20]. So, it is required to recover the carbon fiber polymer composites to reduce the environmental impact due to the waste obtained after its life cycle and manufacturing the recycled carbon fiber (rCF)-reinforced polymer composites in different applications.

The recycling of the CFRPC can reduce the demand for new carbon fiber fabrication, which is energy intensive and emits greenhouse gas emissions. Because of using a thermoset resin and changes in dimensions, form, and kind (fabric or unidirectional material), it is impossible to reuse these carbon fiber prepreg cut-offs, and most end up in a landfill. There is a great need for the capacity to regenerate (recycle) carbon fiber prepreg cut-offs to minimize the unwanted waste of high-value carbon fiber prepregs while lowering the harmful effects of disposal. Consequently, practically all associated advancements are centered on isolating and recovering the rCF from CFRP and utilized as a reinforcement fiber for CFRP [21]. One of the more notable advantages of employing rCF is its beneficial environmental impact. The requirement for fresh carbon fiber to be manufactured is minimized by recovering carbon fiber materials rather than generating fresh ones. As a result, energy is saved, greenhouse gas emissions are minimized, and dependency on nonrenewable resources is lessened. The benefits of recycled carbon fiber are illustrated in Fig. 2(a). Carbon fiber recycling diverts garbage from landfill and combustion, helping to reduce trash and promote a more sustainable economy. The circular economy, formerly called no-waste production, is a manufacturing framework that enables the remanufacturing, reuse, and recycling of items after they have reached their end-of-life (EOL) phases [22–24]. The circular economy method illustration of the CFRPC is shown in Fig. 2(b). It reduces the harmful effects of carbon fiber trash created during production operations or from end-of-life items. Following existing studies, recycling of the CFRP using a chemical technique consumes 60–90 MJ/kg, whereas approximately 198–595 MJ/kg of the total energy needed to make virgin carbon fibers [25]. Recycling of the CFRPC positively affects the circular economy, which causes to reduce the CFRPC waste after its life cycle in different applications. Although their numerous advantages, composite materials are rarely recyclable due to their high strength and durability. The increased pace of composite material production across industries resulted in significant amounts of composite waste, both from manufacturing and end-of-life trash.

Several investigations into carbon fiber recovery from CFRP has been carried out, and many recycling technologies have been established. Different recycling techniques of the CFRPC waste were used to recover the carbon fiber which are employed in the specified application according to the strength of the manufactured part using the rCF. Turner et al. [26] identified some issues confronting recovered carbon fiber composite technology in 2010, stating that fiber orientation would be a significant aspect in manufacturing competitive reused fiber composites. Pimenta and Pinho [27] investigated the recycling of just carbon fiber reinforced plastic for use in construction, as well as the commercial prospects for these recycled materials. Current review works provide the different recycling techniques of the CFRPC [28], potential of the recycled carbon fiber which is obtained from the different sectors and processing of the rCF [29]. Whereas less emphasis have been made on the advancement in the recycling techniques of the recycled carbon fiber using the carbon fiber polymer composites combined with the remanufacturing of the recovered carbon fiber with the different polymer's

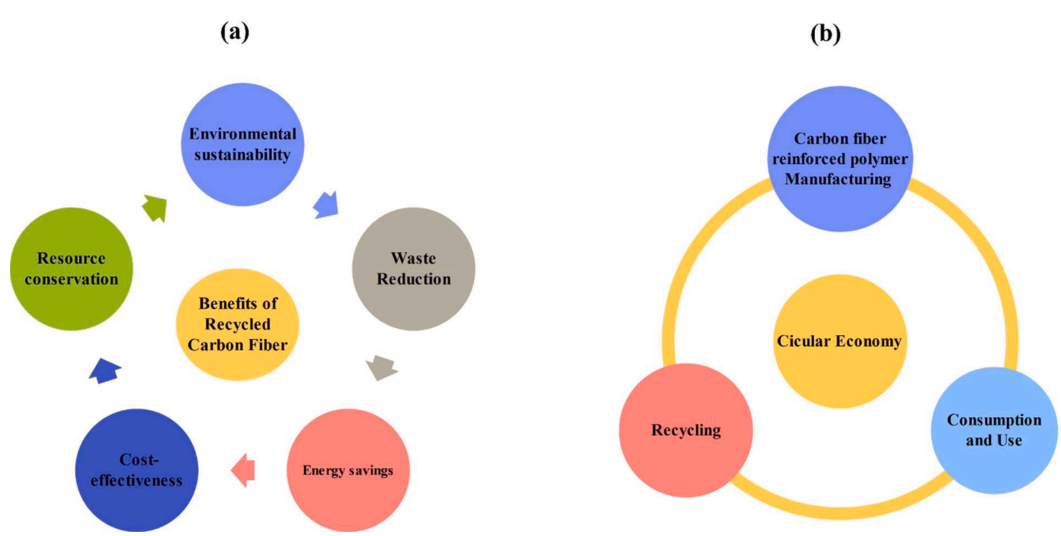

Fig. 2. (a) Benefits of utilizing the rCF, (b) Illustration of a circular economy method for CFRP.

matrix materials. This review paper present the state-of-the-art developments in the recycling technique of the rCF and the remanufacturing of the rCF in the different polymer composites materials fabricated using the fused deposition modeling (FDM) printers. In addition, the future recommendation for the 3D printing of the rCF as reinforcement in the different matrix materials and challenges observed for the recycling and printing of the rCF with the various matrix materials were presented in this work.

2. Recycling of carbon fiber technologies

Carbon fiber recycling is a significant procedure in the composites industry for promoting sustainability and reducing trash. There are three different categories of carbon fiber trash such as i) carbon fiber offcuts created during manufacturing (dry fibers) with mechanical properties similar to vCF, ii) prepreg wastes and partially finished goods, and iii) fibers that can be salvaged from CFRC [30]. The typical recycling process of the carbon fiber obtained from the CFRPC is illustrated in Fig. 3 (a). Several techniques and equipment for recycling and reusing carbon fiber in new industrial goods have been established. In the case of the circular economy, the best quality emerges in the repurposing/reuse or reshaping/resizing of the good or the recovering, recycling, and processing of the recovered material. The summary of the recovered carbon fiber using the different recycling techniques is shown in Table 1.

Furthermore, recycling and remanufacturing new composites for high-end applications is critical for its sustainability [31–33]. The recycling cycle of the CFRPC is shown in Fig. 3(b). Carbon fiber recycling involves many steps that turn waste carbon fiber into usable products. Collecting discarded carbon fiber composites, which can come from various sources, including manufacturing waste, end-of-life goods, or excess materials, is the first step in the process. After gathering, the carbon fiber waste is sorted to remove any pollutants or non-carbon

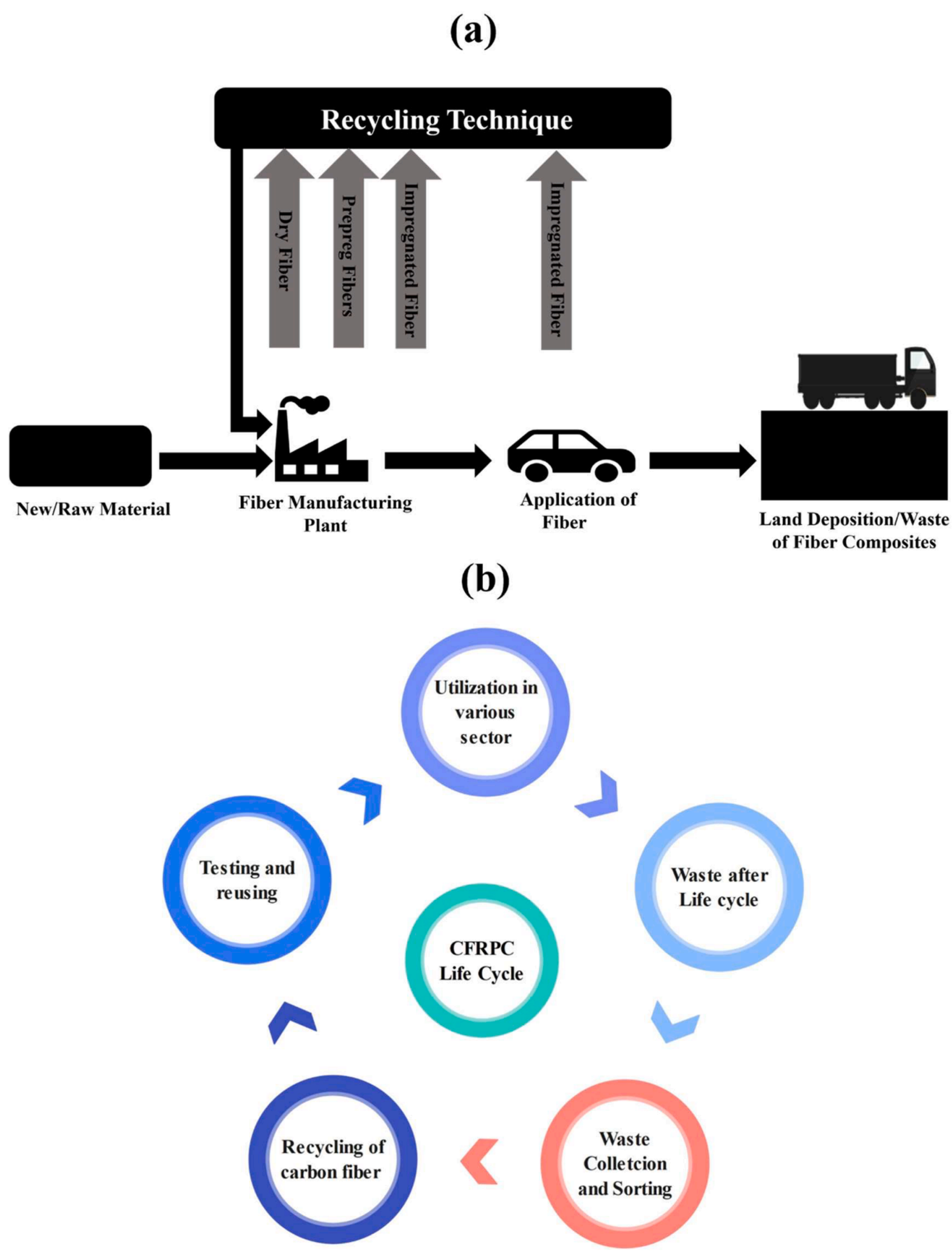

Fig. 3. (a) Recycling process chain used in the industry for recovered rCF (Derived from the [30]), Reproduced with permission from Elsevier, (b) A life cycle illustration of a CFRPC.

Table 1
Summary of the various recycling techniques.

Source	Recycling Technique	Experimental Condition	Strength of the recovered CF	Dimension of rCF Obtained	Outcomes Obtained/Other
[69]	Mechanical Technique	The band saw was used to cut the materials into 20×20 cm sections, which were then put through a TRIA screen-classifier hammer mill with an 8 mm classifier screen.	–	–	The mechanical strength of recovered composites can be increased, and far greater amounts of recycled can be used.
[46]	Mechanical Technique	The solid tool having a diameter of 12 mm and a spindle speed of about 1000 rpm was used.	–	–	Mechanical recycling's unit production energy (2.03–0.27 MJ/kg) is significantly less than the energy content required for virgin carbon fiber (183–286 MJ/kg).
[70]	Mechanical Technique	Grading was done using the hammer mill on the CFRPC waste using the 50–100 mm size cut.	–	Non-Uniform fiber length obtained.	The research discovered that the mechanical recovery of carbon fibers is not economically viable at 4100 USD/ton when contrasted with standard waste treatment methods.
[56]	Thermal Technique	The pyrolysis is performed at 500 °C. Post-treatment: at the same temperature for 60 min. Cure cycle: At 110 °C for 40 min. having pressure 45 bar.	The young modulus and stress at the break were 1.8 ± 0.3 GPa and 93 ± 28 MPa, respectively.	The diameter of the fiber is 6.9 to 6.5 μm.	The gaseous and liquid by-products can support approximately 75 % of the recycling energy needs.
[71]	Thermal Technique	The polymer is extracted from the scrap composite in a bed of silica sand fluidised by air at temperatures above 500 °C.	The tensile strength of recycled fibers was 4896 MPa, which was 18. 2 % lower than virgin fibers.	The diameter of obtained fiber was 4.91 μm	A drawback of this fluidised -bed procedure is the high-temperature air required.
[72]	Chemical Technique	Investigations were carried out in a batch-type reactor (10 mL) without stirring, at temperatures ranging from 523 to 673 K, with pressures varying from 4.0 to 27.0 MPa and reaction periods varying from 1 to 30 min.	The tensile strength of recovered fibers was 90 % to 98 % than that of virgin fibers.	The diameter of the fiber is 7–8 μm.	When running in supercritical conditions (ca. 28 MPa and 673 K), the process yield rose dramatically, reaching 79.3 wt.%.
[73]	Chemical Technique	The carbon fiber was recovered at the temperature of 270 °C, having a pressure of about 80 bar for 90 min using the MeOH.	The recovered carbon fiber tensile strength was reduced by 9 % compared with the vCF.	–	When contrasted with virgin carbon fiber, the interfacial strength of recovered carbon fiber dropped by roughly 20 %.
[74]	Chemical Technique	The epoxy resin in composites dissolved at temperatures ranging from 285 to 330 °CCelsius. The decomposition of CFRP was performed in the molten KOH.	The recycled carbon fibers maintain approximately 95 % of their tensile strength at 330 °C.	–	With higher temperatures, the duration needed for the total decomposition of the resin matrix reduces.
[75]	Chemical Technique	The efficient approach for mild recycling CFRP operating temperature was about 210 °C with the solvent ZnCl2/ethanol catalyst system.	The recovered carbon fiber still retains its high mechanical characteristics.	–	Reclaimed fiber can be an outstanding performance reinforcement ingredient in new composite products.

components and verify the quality of the recycled material. The recycling technique is employed to obtain the rCF, which is then tested for utilization in the different application parts of the various industrial sectors. When the lifespan of a good is complete, and the reused carbon fiber composite material approaches its end-of-life phase, it can be recycled again.

There are several techniques for recovering carbon fiber waste materials, such as recovering fibers as dry fabric waste, recovering non-cured prepreg, or separating carbon fiber from cured CFRP end-of-life products. The following are the recycling techniques [34,35] used to retrieve the carbon fiber shown in Fig. 4. In the recycling approaches, the chemical and thermal recycling processes for treatment can be used on thermosetting and thermoplastic matrices. These technologies principal objective is to remove fiber from the matrix material. However, chemical treatments necessitate massive quantities of solution agents, and the residual washing liquids include solved/corroded polymers that must be thrown off correctly or treated appropriately. Different recycling approaches produced distinct properties of the rCF based on the fiber's length, physical characteristics, and strength. A further explanation of the significantly used recycling technologies of the CFPC is described below.

2.1. Mechanical technique

Mechanical recycling is an approach for recovering carbon fiber-reinforced polymer composites, including crushing, grinding, milling, and shredding. crushing, shredding, milling, or different comparable breakdown procedures are used to reduce carbon fiber waste or carbon fiber-reinforced polymer composites to microscopic fragments. Mechanical recycling primarily minimizes the number of CFRP into tiny pieces via shredding and milling/grinding. Mechanical recycling entails first decreasing the CFRP size to 50–100 mm, typically using slow-speed cutting or chopping mills; garbage is then milled or ground to about 50 m (powder) or 10 mm (fibrous) size [34]: this procedure needs an important quantity of energy since shredding fibers is complex. The traditional recycling machine used to recycle the fiber from the FRPC is illustrated in Fig. 5.

Various researchers [38–41] used mechanical recycling to recover the rCF from the CFRPC after its life cycle. Because the mechanical technique is energy efficient compared to the other recycling techniques like thermal and chemical because it can reclaim the rCF using the low power compared to the other recycling techniques using the CFRPC. The comparison of energy utilization of the different recycling techniques

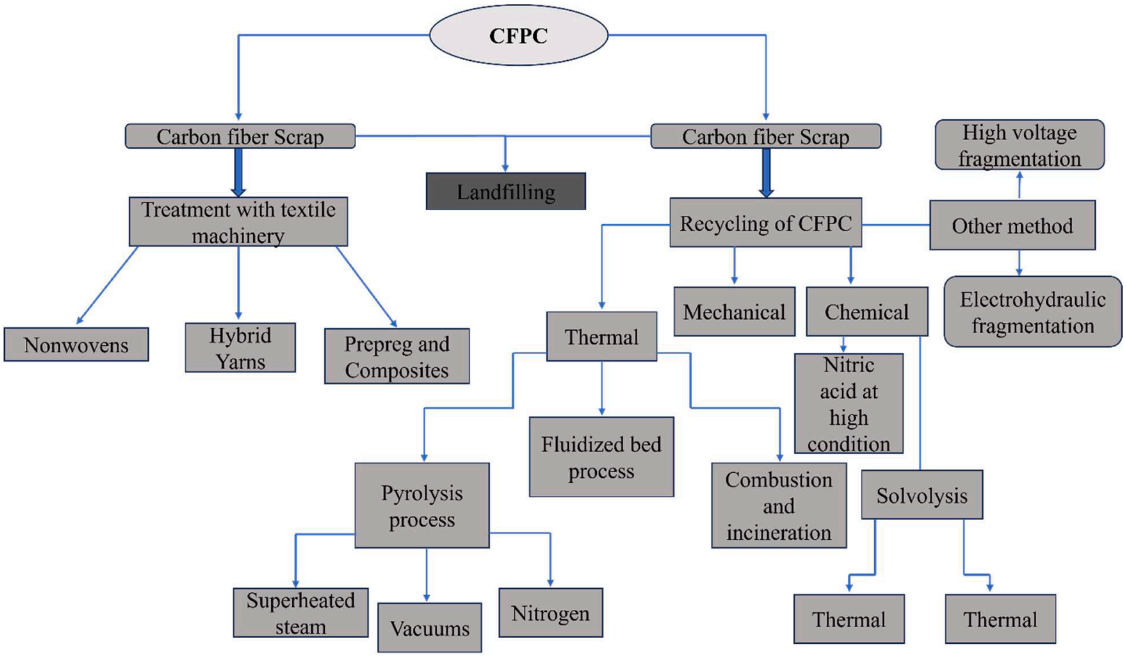

Fig. 4. Different recycling techniques of CFRC waste and dry CF trash.

Fig. 5. Mechanical MAS1 Wittmann granulator recycling machine. Reproduced with permission from Elsevier [37].

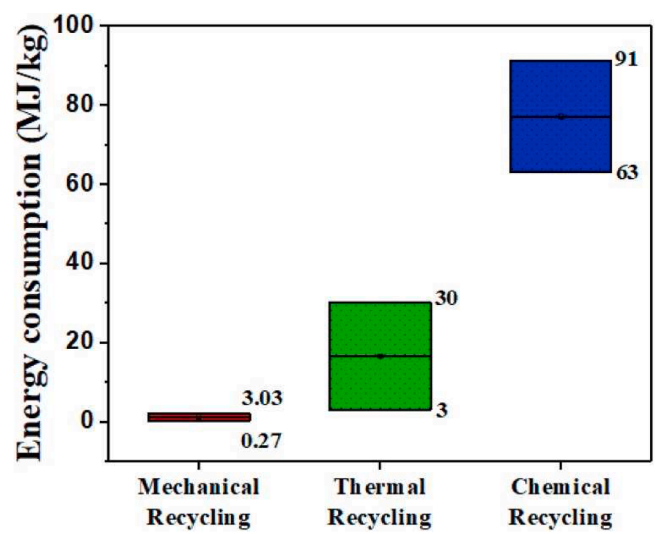

Fig. 6. Energy required for recycling the fiber using the different recycling techniques from the waste of fiber composites after the life cycle. Reproduced with permission from Elsevier [28,43–46].

which is required to recover the rCF from the CFRPC is illustrated in Fig. 6. Due to the low energy utilization required for the reclaiming of the rCF from the CFRPC, and mechanical recycling is an economical recycling technique. One of the limitations of using the mechanical recycling technique is that length of the recovered fiber obtained is shorter, which causes poor bonding between the fiber and matrix materials. The poor interfacial bonding decreased the mechanical characteristics of the final product manufactured using the rCF-like surface condition, tensile modulus, and strength by up to 50 % [42].

The mechanical recovering technique was employed in the initial methods used for recycling CFRP. Mechanical or physical processes are used to grind the CFRP into tiny pieces in the mechanical recycling approach. During these operations, several solid materials are frazzled, crumbled, and broken into small pieces. The following trash could be separated into valuable pitch-powdered and stringy materials by sieve [6]. Palmer et al. [38] developed recycled CFRP materials to replace glass fibers (GF) in a sheet molding compound (SMC). The regenerated composite materials were milled using a rotating hammer milling technique, and the recovered CFs were dimensioned using screening equipment. Then, reclaimed carbon fibers with dimensions ranging from 0.5 to 10 mm were combined with coarse fibers (longer than 10 mm) to create SMC materials. At the end of the experiment, they concluded that this type of recycled material has mechanical qualities similar to those reinforced with virgin glass fiber.

Li and Englund [47] observed the mechanical recycling technique to recover the carbon fiber from the carbon fiber polyether ether ketone (PEEK) composite obtained after the aerospace life cycle. They observed the structural and physical characteristics of the recovered carbon fiber by varying the processing constraints, particle dimensions distribution, and temperature. Owing to the presence of molten peek polymer squeeze-out at more significant pressures, the pressure value used in the present study was between 0.34 and 0.41 MPa. The flexural strength of the recycled carbon fiber composites (rCFC) was roughly 10 % of that of the initially constructed composite, whereas the flexural stiffness of the rCFC created with shredded material was nearly fifty percent of the initial stiffness. Tensile strength enhanced (above 30 % of the original composite), while tensile stiffness remained at 25 % of the original composite. The shredded portion performed best at 390 °C for 16 min [47]. The cooperating enterprise additionally post-thermoformed the created flat sheets. Few research has been published in this field to analyze the parameters of operation and explore potential uses. At the same time, the mechanical recycling of glass fiber-reinforced composites has received more significant interest in research than carbon fiber-reinforced components [48].

2.2. Thermal recycling process

Heat breaks down the scrap composite in a thermal recycling process. Because of the increased temperature of operation (450–700 °C), the unimportant volatile elements will be burned away, keeping only the desirable fibers. Typically, the method's temperature is determined by the kind of resin used in the waste composite. Inappropriate temperature may either cause char on the surface of the reclaimed fibers (undercooked) or reduce the diameter of the reclaimed fibers (overcooked) [36,49].

2.2.1. Fluidised bed recycling

Thermal degradation of the polymer matrix is followed by the dissolution and gathering of individual glass fibers and filler particles in the fluidised bed procedure. To prevent char development, oxygen is essential. The fluidised bed has the potential to be a handy way of quickly heating feed material in an air stream while also providing the destruction required for removing monofilaments from the reinforcing phase. The fibers and filler are then removed from the gas stream, which may proceed to a high-temperature secondary chamber of combustion where the resin is oxidized. Waste composites are crushed to around 25 mm long and put into a fluidised bed. This is a layer of silica sand with particles about 0.85 mm in size. The sand is fluidised with a stream of hot air, with average fluidising velocities ranging from 0.4 to 1.0 m/s at temperatures ranging from 450 to 550 °C [50]. The fiber reinforcement in a composite may have the highest recovered worth.

Over the last ten years, the University of Nottingham's development has focused on developing a fluidised bed method for recovering high-grade and carbon fiber reinforcement from waste glass and carbon fiber-reinforced composites [51,52]. The fluidised bed recovering technique is illustrated in Fig. 7. The outer layer was constructed from three flanged stainless-steel tubes. The bed was made of silica sand and was attached by a perforated stainless-steel mesh. The upper pair of tubes form the freeboard, where the fluidising sand disengages. In a ducting segment with electric resistance heaters (the highest point rating of 43 kW), fluidising air had been warmed to a predefined temperature. The ducting ended in a base bin that baffled and deflected hot air towards the bed. The airflow was manually regulated with a control

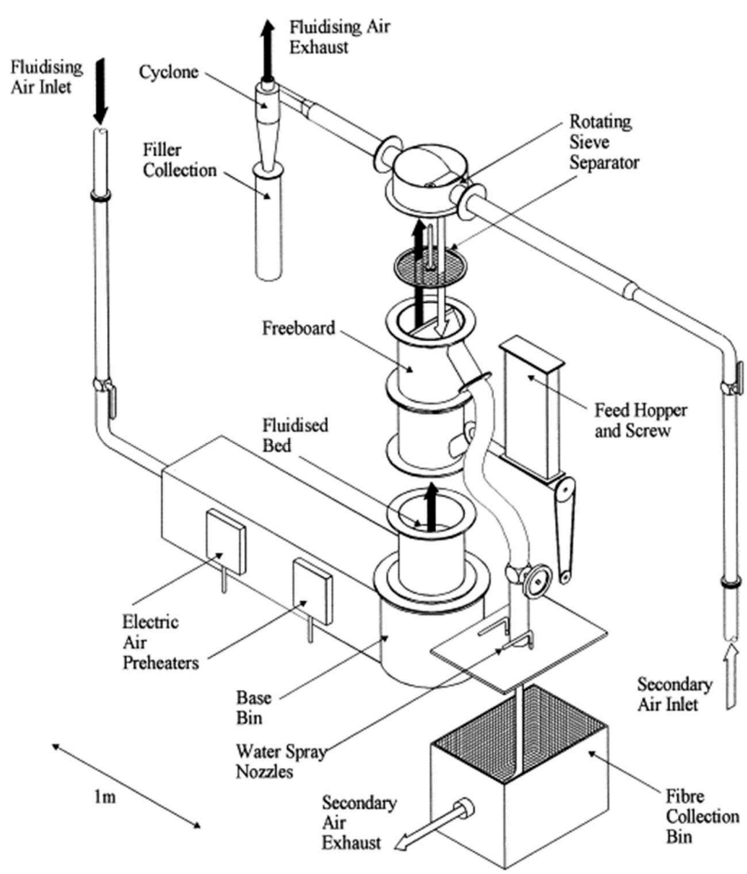

Fig. 7. The fluidised bed CFRP recycling procedures primary elements and flow orientations. Reproduced with permission from Elsevier [52].

valve and monitored with an orifice plate. Compressed feed was kept in a container and supplied by an intake screw at a location over the hotbed.

Meng et al. [25] conducted a life cycle assessment of the carbon fiber recycling procedure in a fluidised-bed system. The composite waste was crushed before using the fluidised-bed technique, which produced fluffy fibers. Under typical workplace circumstances, findings showed that rCF consumed less energy than vCF. The fluidised process's parameters for processing were extensively adjusted to ensure a low energy requirement. They identified the feeding rate per unit bed surface as critical in achieving energy-effective carbon fiber recycling. Furthermore, the energy analysis showed that the energy needed for rCF generation was relatively low compared to vCF under typical operating conditions. Using rCF in high-value structural applications significantly reduced life cycle power and emissions of greenhouse gases (GHG) significantly.

2.2.2. *Pyrolysis*

Pyrolysis is a chemical reaction that includes the heat degradation of organic compounds without oxygen, such as biomass, trash, or polymers. The organic elements of the composites are broken down during the pyrolysis process, enabling the carbon fiber to be isolated and recycled for use in new applications. The pyrolysis technique provides the rCF with high-quality properties comparable to vCF. The substance is subjected to elevated temperatures during pyrolysis, ranging from a couple hundred to over a thousand degrees Celsius. Without oxygen, the substance performs a chemical transition rather than combusting. Depending upon the kind of composites and reinforcement materials, the treatment temperature is typically between 400 °C and 1000 °C [53–55]. This temperature is sufficient to deteriorate even carbon fiber. The liquid materials generated (tar and other heavy liquids) can be utilized to make oil or various other goods. Gaseous outputs (e.g., CO2, H2, CH4, and other hydrocarbons) have a low calorific value but can nonetheless self-sustain the process as a source of electricity.

Furthermore, Meyer et al. [53] recovered the carbon fiber from the CFRPC from the aircraft after its life cycle. They optimized the low-efficiency lab scale to a semi-scale level pyrolysis process. They could replicate semi-industrial manufacturing procedures using a larger oven. Although the rCF was sufficiently successful to substitute the vCF, an additional heating system was installed to remove the leftover char. Generally, a regulated environment in the pyrolytic reactor can influence the method's outputs. The recovered carbon fibers from this process offer an excellent chance for substituting fresh carbon fibers in CFRP goods, allowing the CFRP cycle to be closed.

Researchers used the pyrolysis process to recycle the rCF from the CFPC waste obtained after its life cycle. Giorgini et al. [56] used the pyrolysis recycling technique to recover the carbon fiber from the CFRPC. Fibers for *Re*-CCFRC are quickly recovered using dimensionally inconsistent pyrolytic leftovers derived from the trash of varying forms and fiber kinds. The fiber was oxidized at 500 °C for 30 min; they are only identifiable in the specimen treated for 10 min. The reclaimed fibers have been cut to a sufficient length oxidized, if necessary and impregnated with a two-component epoxy resin composition (feed: CCF/resin 1/1 ratio). The immersion procedure was done directly, and the resulting solution was loaded into a steel mold (200 × 150 mm) that was placed in a hot plate pressed at 110 °C and 45 bar pressure for 40 min. The obtained composites were cut into the appropriate panel for further analyzing the mechanical strength of the rCF obtained. Guo et al. [57] used the pyrolysis oxidation two-step process to obtain the recycled carbon fiber and identified that pyrolysis has been an efficient process of the recycling CFRPC. The findings demonstrate that carbon fibers reclaimed via pyrolysis at 600 °C for 30 min and oxidation at 450 °C for 15–20 min have higher mechanical characteristics. Tensile strength may achieve 90.19 % of vCF, tensile modulus can exceed 84.44 % of vCF, electrical conductivity can achieve 70 % of vCF, and recovery rate can exceed 95.22 %. The recycling process of the carbon fiber from the CFRPC is shown in Fig. 8.

Kim et al. [58] altered the pyrolysis procedure by exposing the CFRC to 550 °C superheated water steam for 30 min. This was followed by a 30–75 min air oxidation method at 550 °C. Instead of volatile chemicals, this process created high molecular weight tar, which attributed to lower carbon dioxide emissions. After 75 min of oxidation in air, the rCF surface was fresh, but shorter oxidation durations resulted in resin leftovers on the fiber surface. When contrasted with vCF, the tensile strength and IFSS values of rCF were 90 % and 115 %, correspondingly. The recovered performance of rCF from composites was highly influenced by decomposition temperature, reaction duration, and superheated steam supply frequency. In the framework of recycling management, Hagnell and Akermo [59] proposed employing trash as assets, solutions such as no-waste and no-waste production. The prospective benefits of such a closed-loop system are numerous, comprising advanced recyclability, resource efficiency, conversion of energy, and most likely, lower raw fiber reinforcement costs. The researchers concentrated on evaluating and discussing minimizing the material expenses associated with recycled fibers reinforced composites brought into structural use. Their model for waste and reusing operation provided critical information for industrialists and academics by establishing a link between the price of raw materials, novel composites made from recycled fiber, and mechanical efficiency. Overall, each fiber's various characteristics and attribute values are recovered in bulk within the same procedure, resulting in a batch of fibers with multiple characteristics [36]. As a result, sorted pyrolysis and laboratory-scale pyrolysis produce higher-quality recovered fibers than those used in industrial manufacturing.

To reuse trash CFRP, Ye et al. [60] devised an optimized steam thermolysis method incorporating vacuum pyrolysis and mild gasification. The technique kept 90 % of its tensile strength in all laboratory and semi-industrial levels. According to the investigation, a rise in deterioration in the polymer matrix led to a drop in the tensile strength of the fibers. This demonstrates the viability of recovering high-quality residue-free carbon fibers using improved steam thermolysis. Furthermore, Carbon Conversions Ltd., ELG Carbon fibre Ltd., Karborek Ltd., Mitsubishi Ltd., and others are among the largest carbon fiber recycling manufacturers in the worldwide marketplace. ELG Carbon Fiber Ltd. regenerates carbon fibers that retain a minimum of 90 % of their tensile strength, but at a price that's 40 % less than industrial carbon fibers, with a carbon fiber reusing price of only $15/kg when the ability attains 100 tons/year [61].

2.3. *Chemical recycling process*

Chemical and associated electrochemical CFRP procedures for recycling employ a wide variety of solvents, including supercritical and subcritical, and are frequently carried out at ambient pressures. The chemical regeneration of CFRPC entails modifying the chemical composition of the scrap material to convert it into new components that may be utilized as raw materials in the production of plastics or other goods. At specific temperatures, ultrasonic solvolysis in diluted nitric acid and hydrogen peroxide can also reach a polymer matrix degradation extent of 95 % with excellent efficacy. Acetone and hydrogen peroxide, dimethylformamide and hydrogen peroxide, and a peracetic acid aqueous mixture produced recycled carbon fiber with a matrix degradation of 90 % to 97 % [34]. Rigid CFRP is initially shredded to boost the surface area that comes into contact with the solution and enhance matrix dissolving; at the end of the procedure, the rCF is washed to eliminate degraded polymeric components and solvent residual [62,63].

Some of the key benefits of this technology include: First, getting clean fibers with minimal mechanical property degradation; second, retaining the length of fibers fed to the reactors; and lastly, quick and specific depolymerization [64]. Even so, this recycling method is costly since it necessitates using particular reactors and facilities capable of functioning at elevated pressures and temperatures and with the help of

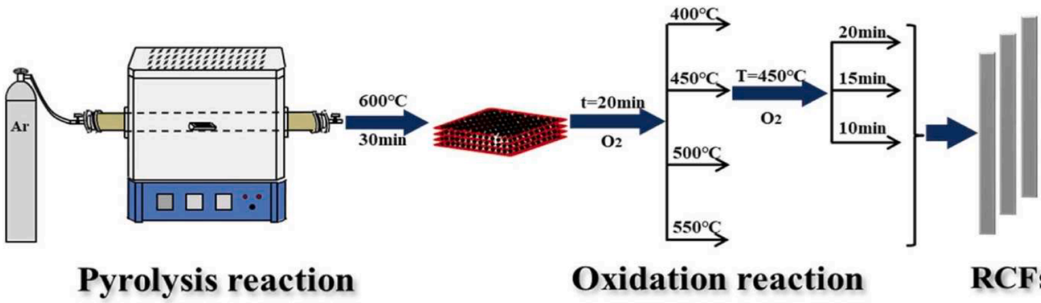

Fig. 8. Schematic diagram of the carbon fiber recovery using the pyrolysis process. Reproduced with permission from Elsevier [57].

corrosive media [36]. Zhu et al. [65] employed an electrochemical regeneration approach in which CFRP composites were submerged in a NaCl electrolyte, including the KOH catalyst, while electrical currents were applied. The C—N bonds of the epoxy resin were broken by an electrically driven catalytic reaction, resulting in matrices disintegration via the electrochemical encouragement of catalysis impact. Given ambient temperature and pressure, traditional, non-toxic chemicals were utilized in this approach, which achieved near 100 % resin removal and a strength retention rate of close to 90 % for the regenerated carbon fibers.

Numerous studies have employed subcritical or supercritical solvents to substitute these compounds at various temperatures and pressures, such as water, alcohol, ammonia, and organic solvents, to alleviate these problems with the environment. Solvent decomposition is another name for the chemical recycling technique of supercritical fluids. Das et al. [66] used a one-step oxidative process for reclaiming the CFRPC trash obtained from the aerospace sectors. The treatment of the peracetic acid [H2O2 + CH_3COOH] is used to recover the epoxy resin and carbon fiber from the CFRPC. Single fiber tensile tests performed on virgin and recoverable fibers yield comparable results, demonstrating that exposing fibers to a combination of H2O2, PAA, and acetic acid has no negative effects on fiber strengths. A putative response mechanism for epoxy matrix breakdown is given. With a recovery effectiveness of more than 90 %, all solvents used were recovered in their original and recyclable type. With no appreciable loss of tensile strength, the reclaimed epoxy was utilized alongside an adhesive-grade epoxy (2 wt.%). At specific temperatures, ultrasonic solvolysis in concentrated nitric acid and hydrogen peroxide can also reach a polymer matrix degradation rate of 95 % with excellent efficacy. Acetone and hydrogen peroxide, dimethylformamide and hydrogen peroxide, and a peracetic acid aqueous mixture produced recycled carbon fiber with a matrix degradation of 90 % to 97 % [66].

The specimens were placed into the glass beaker that had a small quantity of acid solution (sulfuric and nitric acid, etc.) to expand and delaminate. Each of the samples should be immersed in a solution of acids at ambient temperature for the required amount of duration. The immersing solution in this work was nitric acid, and it was discovered that nitric acid can speed up the aging of the CF/EP. After acid pretreatment procedures, the smooth resin surface of the CF/EP had a rough and coarse surface, and the CF/EP appeared stratified [67]. The chemical recycling process is illustrated in Fig. 9.

Liu et al. [68] discovered that nitric acid outperformed sulfuric and hydrochloric acid in dissolving thermoset epoxy resin and recycling neater carbon fiber. Furthermore, the orthogonal investigation was performed to demonstrate the reusability of regenerated carbon fiber and even harder resins, such as amine-cured epoxy, were destroyed using nitric acid. They investigated that the most appropriate combination was a breakdown room temperature of 90 °C, an acid solution concentration of 8 M, and a specimen mass to acid solution volume proportion of 4 g:100 ml.

3. Remanufacturing and reusing of the rCF using different recycling technique

The method of restoring used or broken-down goods or parts to their original state is known as remanufacturing. This procedure can reclaim carbon fiber from carbon fiber-reinforced composites using different recycling techniques and utilized again for remanufacturing. Remanufacturing is an appealing strategy for reclaiming carbon fiber from composite trash and minimizing the composites industry's environmental impact and cost of the carbon fiber. Different recycling techniques are utilized to recover the carbon fiber from the CFRPC and remanufactured using the virgin polymer using the FDM technique. There is no comparison between the rCF and vCF-reinforced polymer composites printed parts using the 3D printer because of the lower mechanical properties of the rCF-reinforced polymer composites parts. The rCF-reinforced polymer composites, on the other hand, are feasible in terms of cost, weight savings, and the creation of complicated designs.

The remanufacturing of the carbon fiber using the FDM technique makes the sustainability manufacturing of the CFRPC parts, which is

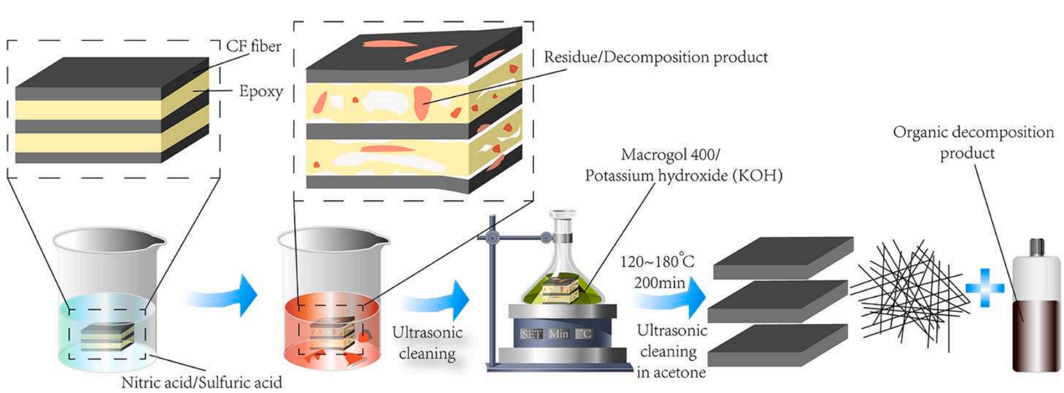

Fig. 9. Schematics depict the CF/EP breakdown procedure using chemical recycling. Reproduced with permission from Elsevier [67].

utilized in the different industrials sector according to specific strength requirement. Researchers used the recovered carbon fiber obtained from the different recycling approaches in the different polymer's matrix having the different content of the rCF. Based on the recycling and remanufacturing of 3D printed continuous carbon fiber reinforced (CFR) PLA composites, a more environmentally friendly fabrication strategy for excellent performance continuous carbon fiber reinforced thermoplastic composites (CCFRTPC) has been developed [76]. Remanufactured CFRTPC samples also had a 25 % better-bending strength than initial ones, demonstrating the initial non-downgrade reusing technique for CCFRTPC. A material recovered percentage of 100 % for continuous carbon fiber and 73 % for PLA matrix was attained for a lower ecological impact. A closed room for recycling could be more effective, but storing the entire composites in a warmer environment would worsen the matrix's aging phase. A suitable recycling technique is still being researched. In any case, even with the existing configuration, the energy required for recovering is significantly less than that required for producing fresh carbon fiber. When the reuse and recycle strategy is optimized, the resulting energy savings will be more significant [76].

Liu et al. [77] remanufactured and reclaimed the carbon fiber using the supercritical N-butanol in the closed-loop recycling technique. To assess the ability to be reused of the rCF and the possibility of the closed-loop recycling procedure for carbon fibers, the rCF were combined with fresh epoxy resin and polypropylene to remanufacture the composites, and the mechanical characteristics of the remanufacture composites were evaluated during the procedure of remanufacturing. The manufactured rCF filaments had an excellent tensile feature with a tensile strength retention percentage of 95.17 % and a tensile modulus retention percentage of 93.17 %. Remanufactured rCF/EP composites part with identical carbon fiber percentages demonstrated slightly poorer mechanical characteristics than parts fabricated using the vCF/EP composites. Remanufactured rCF/PP composites with exact carbon fiber percentages exhibit more excellent tensile and flexural strengths than VCF/PP composites. Tensile strengths of regenerated rCF/PP composites increased by 9.2–12.84 % [77]. Su et al. [78] fabricated the rCF in the PA matrix materials at the different content (10 wt.%, 20 wt.%, 30 wt.%, and 40 wt.%) in the FDM printers. The greatest improvement in the tensile strength was observed using the 20–30 % of the rCF in the PA polymer composite materials. The tensile strength and tensile modulus of the part fabricated using the rCF/PA composites is illustrated in Fig. 10. The summary of the rCF remanufacturing using the different polymers obtained from the different recycling technique in the FDM printer is illustrated in Table 2.

Furthermore, the remanufacturing of carbon fiber is investigated in more detail. Cheng et al. [79] remanufactured the rCF from the virgin carbon fiber polylactic acid (vCF/PLA) composites using FDM. The vCF and rCF are wet and processed into chopped fibers in a ball grinder. The ball milling jar revolution rate was 400 r/min, and the grinding time was 2 h. The PLA granules are mixed well with chopped vCF and rCF at an appropriate mass ratio. PLA elements, vCF combinations, and rCF combinations are extruded into wires needed for FDM. The dual screw rate has been configured at 400 r/min. At 190 °C, three distinct sets of cables with a wire diameter of 1.75 mm ± 0.2 mm (PLA, vCF/PLA, and rCF/PLA) are blown out with the help of the traction and cooling devices. The bending force of vCF/PLA composites grew by about 7.8 %, the flexural modulus improved by around 81 %, the bending strength of

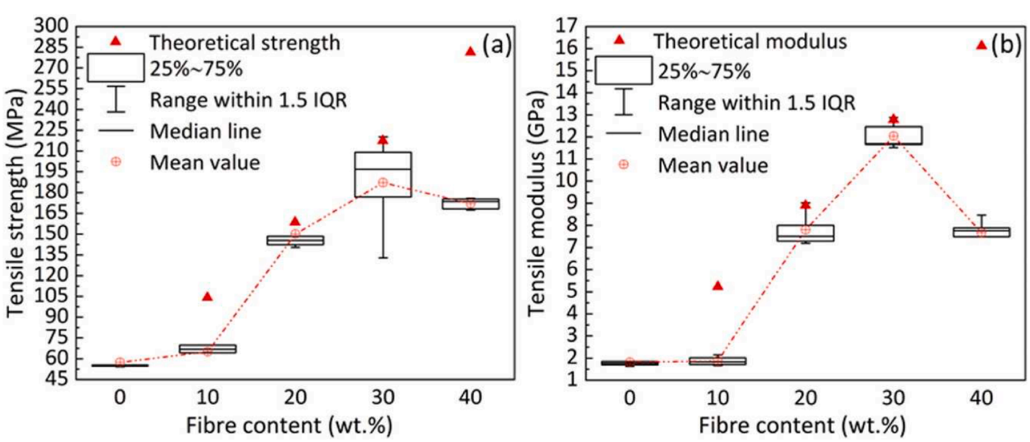

Fig. 10. Mechanical properties result of the fabricated part: (a) Tensile strength of the printed part; (b) Tensile modulus of printed part. Reproduced with permission from Elsevier [78].

Table 2
Summary of the rCF remanufacturing obtained from the different recycling techniques using the different polymers matrix materials.

Matrix Materials	Recovered CF Reinforcement Content	Mechanical Properties	Main Points	Ref.
PP	The recovered carbon fiber content varied from the 10–40 wt.% in the rCF/PP.	The tensile properties of the remanufactured RCF/PP composite increased by 9.2–12.84 %, while their flexural properties increased by 1.96–15.74 % as compared to the vCF/PP composites remanufactured at the same carbon fiber content.	The increase in the carbon fibers content in the rCF/PP composites caused a gap which lead to a decrease in mechanical performance.	[77]
PLA	The content of recovered carbon fiber used is 8.9 vol%.	The flexural strength obtained was 263 MPa.	A novel remanufacturing technique manufactured the filaments of the remanufactured carbon fiber, which has been tensile forced than the original.	[76]
PLA	The 15 grams of rCF was used in the 500 grams of rCF/PLA composites.	The tensile and flexural strength of the composite was about 28 and 85 MPa, respectively.	The monofilament tensile properties of the rCF composites were 8 % higher than the part manufactured using the original carbon fiber composites.	[79]
PA	Different weight percentages of rCF 10, 20, 30, and 40 % were used.	The maximum tensile strength and modulus were superior by up to 175 % (to 150 MPa) and 329 % (to 7.8 GPa) compared to the unreinforced material at 20 wt.%.	By increasing the fiber content, the degree of fiber alignment tends to reduce due to the poor mechanical properties obtained at high fiber content.	[78]

rCF/PLA composites grew by 10.4 %, and the flexural modulus enhanced by 87 % when contrasted with PLA [79]. The complete remanufacturing process of the rCF is illustrated in Fig. 11. The carbon fiber was recovered from the CF/EP composites using the supercritical n-butanol which can degrade the epoxy matrix effectively. The rCF was then printed using the thermoplastics polymer to produce the filaments which was used in the FDM printer [80].

4. Challenges

CFRP Composite recycling is necessary for sustaining such a significant investment in the mixed area. The recycling of carbon fiber from the CFRPC after its life cycle using the different recycling techniques provide the several advantages, including environmental, educational, health, social, and financial advantages. Using the rCF in the different applications required fewer natural resources, less power consumption, and less labor for manufacturing than virgin carbon fiber. The use of the rCF-reinforced polymer composites in different applications also reduced the emission of hazardous gases which has a harmful impact on the environment compared to the utilization of the vCF-reinforced polymer composites in the various sectors. Even so, as a result of the recycling procedure, the tensile strength and surface qualities of rCF were degraded, making reuse of recycled fiber a difficult task. Whereas there are some challenges for the utilization of the rCF with the different matrix materials, some of them are illustrated below:

- The obvious point of view was that the primary impediments to adopting CFRPC composites recycling processes were expense and a lack of industries. Still, the new law was the key mover toward recovery. The main difficulty is that the costs of either mechanical or other thermal recycling processes indicate that the currently generated recycles are too costly to provide a precise market benefit compared to existing alternatives [81,82].

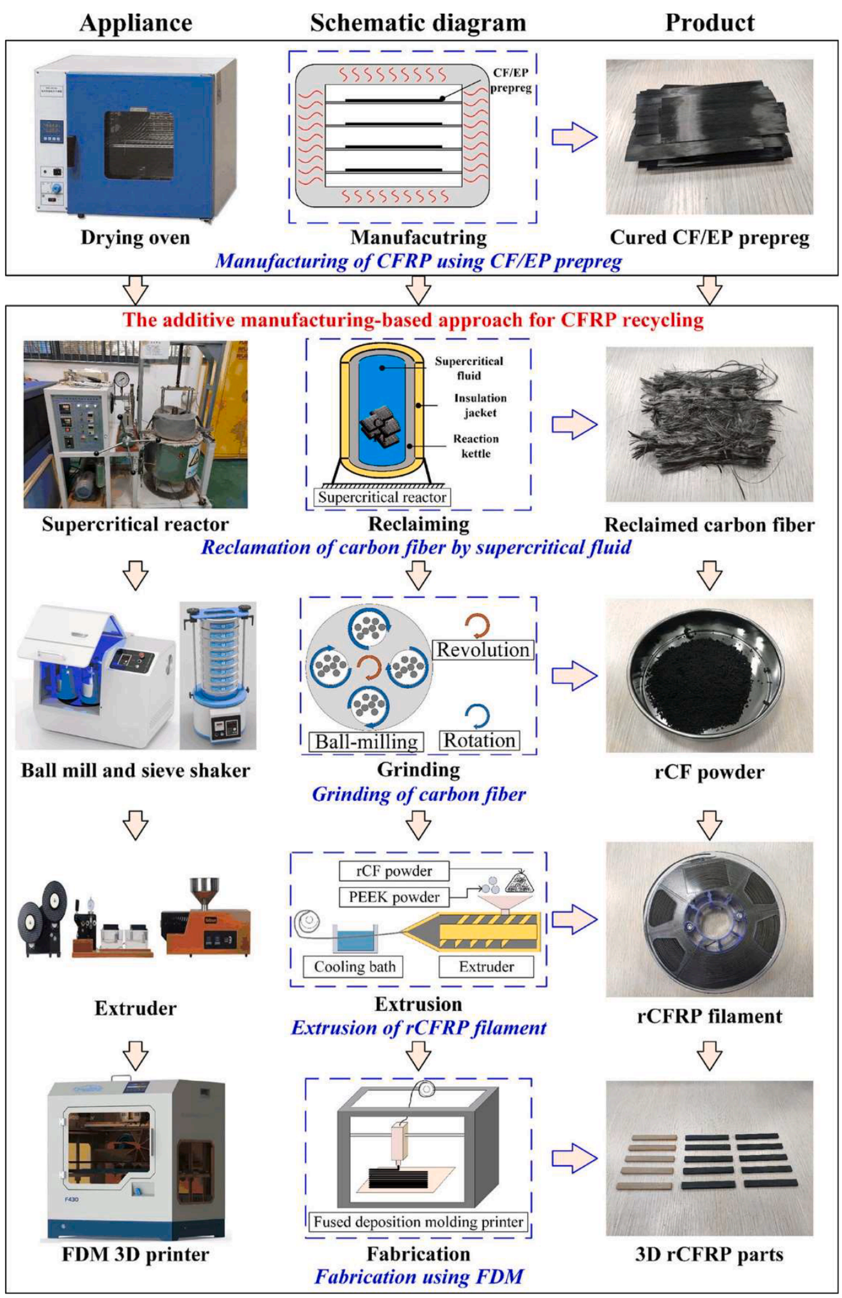

Fig. 11. Schematic diagram of the remanufacturing process of the rCF from the CF/EP using the FDM. Reproduced with permission from Elsevier [80].

- Carbon fibers can be damaged and degraded throughout the recycling procedure, resulting in a loss in mechanical characteristics of the part printed using rCF compared to part printing using vCF. It is critical to retain the quality of carbon fibers throughout regeneration to guarantee their continuing usability [83]. So, post-treated reclaimed carbon fiber is required to enhance the mechanical properties of the rCF.
- Contaminants such as resins, coatings, or other components may be present in carbon fiber-reinforced polymer composites. These contaminants can be hard to remove during the recovery procedure and may impact the overall performance of the recovered carbon fibers. Therefore, there is a need to remove the contamination present in the CFRPC during the recycling technique.
- Recovering carbon fiber from polymer-based composite materials remains a challenge, regardless of significant advancements in this field, because the polymer-based composite is composed of two or more different materials like matrix and fiber reinforcement materials which make the different phases during the manufacturing. Because of the strong interfacial bond between the fiber and matrix materials, separating the fiber during the recycling process is not easy. Despite the great emphasis on recycling carbon fibers from waste products, recovering disintegrated polymer matrix is difficult.
- Different factors influence the output of the recycling process, such as the matrix materials, fiber content, percentage of the matrix materials, temperature, and the waste structure, which make the recycling process challenging to obtain high-performance fiber. So, there is a need to analyze these factors before the recycling process; otherwise, recycled carbon fiber does not provide good mechanical properties.
- During the recycling process of carbon fiber, some recycling techniques use chemicals that can pose health and safety risks to labor and the outside environment. Proper handling of the disposal of used toxic chemicals during the recycling process is necessary to make a sustainable recycling process.
- Although the manufacturing of the carbon fiber recycling reinforced with the polymer composites using the FDM printer provides strength comparable to the mechanical strength of the virgin carbon fiber polymer composites, there is limited manufacture of the content of the recovered carbon fiber with the different polymers in the FDM printer, so optimizing the FDM technique for employing the recovered carbon fiber reinforced polymer composites in high-performance applications is required.

To address these issues, there is required to optimize recycling procedures, which increase the fiber rates of recovery, enhance the performance of fibers, establish sustainable and cost-effective recycling technologies for recovering the carbon fiber from the CFRP composites waste.

5. Conclusion and future recommendations

In this research, several CFRP recycling processes (such as mechanical, chemical, and thermal procedures) and their influencing variables were evaluated, as their impact on the mechanical and physical characteristics of rCF. CFRP composite recycling is a significant concern in terms of the environment and cost for the long-term use of lighter composite materials in transportation, building, and sporting goods. In addition to these technologies, pyrolysis and mechanical treatment show the most promise for utilization in industrial-scale purposes. Furthermore, this study also discusses the advancement in recycling technologies and remanufacturing of the recovered carbon fiber with the different polymer matrices using the FDM printers. Following a systematic review of the literature on the recycling technique of carbon fiber and remanufacturing of the recovered carbon fiber in the different polymer's matrix materials, the following future research suggestions are offered:

5.1. Optimization of additive manufacturing based recycling approach

The present recycling technique based on additive manufacturing produced carbon fiber particles with lower length and quality obtained from the CFRPC after its life cycle. So, there is a need to optimize the recycling technique based on additive manufacturing to enhance the fiber length and the quality of the rCF obtained from the CFRPC waste. Future work will focus on optimizing an additive manufacturing based CFRP recycling approach and expanding the rCFRP framework, such as modifying the grinding procedure to regulate the particle size of the rCF powder and investigating the impact of the rCF addition amount on the functioning and efficiency of the manufactured rCFRP engineering components. So further research will be developments in the recycling process for archiving high-performance rCF with the least environmental footprint.

5.2. Higher volume content of rCF

Manufacturing the rCF as a reinforcement with the different polymer matrix materials can provide the mechanical strength of the part comparable to the part manufactured using the vCF-reinforced matrix materials. Manufacturing the higher volume fraction of the rCF is required to make the strong interfacial bond between the rCF with the polymer matrix materials for achieving the effective mechanical strength of the part. Printing the rCF with the higher volume faction is required to achieve the mechanical qualities, and significant translation of fiber characteristics will be the future research direction.

5.3. Higher production volume

Recycled carbon fibers are now mainly employed in high-volume, low-value filler products. A deficiency of beneficial uses for recycled carbon fibers is a major cause of a shortage of rewards to recycle composites. Similarly, using reclaimed carbon fibers with deteriorated physical characteristics (or even the perceived usage of a lower-quality material) instantly creates a barrier to justifying recovery from a financial standpoint. To generate a motivation to argue for recovery, new and novel fields of study employing this material as a feedstock must be explored. These could be in non-structural ultimate usage that is not normally related or linked with composites.

5.4. Post-process surface treatment

The carbon fiber was reclaimed from the waste of the CFRPC using various recycling techniques, which are then manufactured using the different matrix materials for utilization in the different sectors. But the mechanical properties of the part manufactured using the recycled carbon fiber were not comparable to that of the vCF. So, the mechanical strength of the rCF manufactured part will be increased by the surface treatment, which tends to enhance the interfacial bonding between the carbon fiber with the matrix materials. Same as that Wong et al. [84] studied the influence of coupling agents on recovered CF's capability as a reinforcement for PP composites. The incorporation of maleic anhydride grafted polypropylene (MAPP) increased interface adhesion. Because of the increased interaction between the CFs and matrix, the impact strength of the composites increased dramatically when MAPP was introduced. The increase in composite modulus was attributed to integrating a stronger MAPP and accomplishing stronger interfacial bonding.

5.5. Development of economic recycling approach

Recycling carbon fiber-reinforced polymer composites at a reasonable cost is a big problem for small-scale recycling plants. Recycling operations must create recycling techniques that can compete with the price of fresh carbon fibers while meeting the market's needs. For this purpose, there is a need to develop an economical recycling technique that will be able to recover the carbon fiber from the CFRPC waste at a small price. There is a need to develop a novel remanufacturing technique based on the FDM that helps in green environment manufacturing using the waste of the CFRPC, which provides the effective part fabricated using the rCF having good strength.

5.6. Developing the high-value application of composites using rCF

The manufacturing of the rCF as a reinforcement with the different polymer matrix provides the part which has only limited application in the different sectors which makes the limitation for the manufacturing of the rCF using the different polymer matrix. Therefore, employing the rCF with different matrix materials for high-value applications is an emerging field for prospects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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